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# SANDERLING

## FINAL REPORT : Executive Summary

A Research Study into KBS for Command and Control  
in Naval and TMD Applications

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The SANDERLING Final Report comprises the following three volumes :

- The **EXECUTIVE SUMMARY** provides an overview and summary of the study, including its conclusions and key findings, but not including specific detail on suggested projects;
- **PARTS A & B** cover the method and direction of the study, and include details of the technology analysis as well as the initial thinking behind the projects;
- **PART C** of the Final Report defines the recommended research programme in some detail. It describes suggested projects (including form, content, cost and resources), overall programme structure and recommendations on how to proceed.

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# SANDERLING

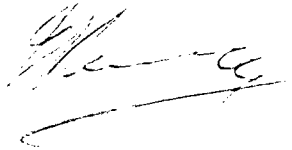
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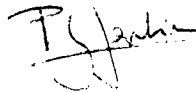
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## SANDERLING Final Report : EXECUTIVE SUMMARY

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## **Executive Summary**

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## 1. INTRODUCTION

Recognizing the potential to be gained in command and control (C<sup>2</sup>) systems from knowledge based systems (KBS) and related techniques, the Admiralty Research Establishment (ARE) set up the Technology Demonstrator Programme (TDP) and the associated Technology Demonstrator System (TDS). This work is addressing many of the practical and immediate problems associated with the application of KBS to Data Fusion in the context of naval C<sup>2</sup>. The ARE programme includes sea trials and supporting research as well as prototypes, theoretical studies and experiments aimed at establishing a wide capability in KBS-based C<sup>2</sup>.

Many of the functional characteristics and technical problems associated with Naval C<sup>2</sup> are similar to those in other large and complex military applications. In particular it was realised that there was significant commonality with the Strategic Defence Initiative (SDI)/Theatre Missile Defence (TMD) scenario. As a result a joint approach to research in KBS technology was agreed between ARE and the SDIO/SDIPO. A major part of this approach is a programme extending over a total of four years. The programme will link to the current ARE research activities and consists of a study followed by a number of research projects to be undertaken by ARE and UK industry and universities.

The first phase is a 6 month study to define the contents of the second phase, a three year research programme. The study commenced in October 1989 and is code-named SANDERLING. It has been undertaken by a consortium of three companies, working in close association with ARE and the SDIO. The consortium comprises Logica Cambridge Ltd, British Aerospace Ltd (Sowerby Research Centre) and Cambridge Consultants Ltd. Logica are the prime contractors and overall project managers.

The aim of the SANDERLING study is to generate a KBS research programme in C<sup>2</sup> for naval and TMD applications.

The results of the study are being reported in an Executive Summary and a Final Report in three Parts. Parts A and B concentrate on the analysis phase of the project. Part A introduces the requirements of the study, the goals and objectives of the work and the approach and methods used. Part B shows how the six technology research streams for the programme were generated and explores the research issues and priorities for sub-topics within each technology stream. The analysis is complemented by an applications perspective and culminates in a set of initial ideas for SANDERLING research projects. Part C uses the results and data from the earlier work to define and evaluate a set of research projects. This forms the recommended research programme, outline plans for which are provided.

The Executive Summary is a stand-alone document. It outlines how the study was carried out, summarises the results of the analysis, and sets out the programme recommendations.



The SANDERLING consortium wish to acknowledge the support given to the project by staff at ARE, the SDIPO, the SDIO and their associated contractors. We are also grateful for the help and advice we have received from many others, including our own external consultants on the Technical Review Panel, and the members of The Electronics and Business Equipment Association, who contributed valuable background material to the study.

## 2. THE STUDY

The terms of reference of the study and the method used to carry it out are summarised.

### 2.1 Terms of Reference

The study was required to recommend a set of research projects that:

- have a combination of near-term and long-term objectives;
- indicate goals and the manner in which they are to be investigated;
- have an identified cost-effectiveness or risk/reward ratio;
- present options to a value, in the region, of £15M from which a programme of value £7M could be constructed;
- represent an interlocking set of topics with a clear strategy to guide choice;
- consider all UK expertise;
- cover an elapsed time of three years.

The study was asked to concentrate on existing relevant work, or ideas of interest within the UK. No specific effort in the study was to be expended in seeking information on US programmes. The findings of the study were reviewed by a Technical Review Panel of leading academic consultants.

There was a strong interest in capitalising on the ARE experience gained from existing data fusion, situation assessment and resource allocation work, and extending this to deal with the requirements of strategic and tactical missile defence and the higher functional levels of C<sup>2</sup>. The study was to take account of the objectives and status of existing and planned ARE projects in the field, including the TDS and TDP, and ARE commitments to projects were to be reflected in the proposed research programme. ARE experience has indicated that much of the research needs to be iterative, learning from previous projects and adjusting the future programme to respond to the lessons learnt. The proposed projects and programme should allow for this in terms of dependencies and reviews.

The study was asked to consider, but not to be restricted by, six specific areas for research: parallel computer architectures, human-computer interaction, validation and specification, database/KBS interfaces, planning and operational TMD applications.

The main SDI assumption was that the primary interest and scenario driver for this work is Theatre Missile rather than Strategic Missile Defence. Thus the main input to the study was to be from UK generated TMD documents. In particular, the SANDERLING study was to complement the UK Architecture Study (UKAS), especially in the areas of discrimination and architecture specification. However, because of the limitation of UK documents and their associated scenarios, the study was also to take some note of strategic defence issues.

## 2.2 Study Approach

The study was carried out in three stages :

- Definition - establish the goals and objectives of the research programme;
- Analysis - explore a wide range of potential research areas;
- Programme Definition - generate a realistic programme of projects.

The relationships between the stages are illustrated in Figure 2.1.

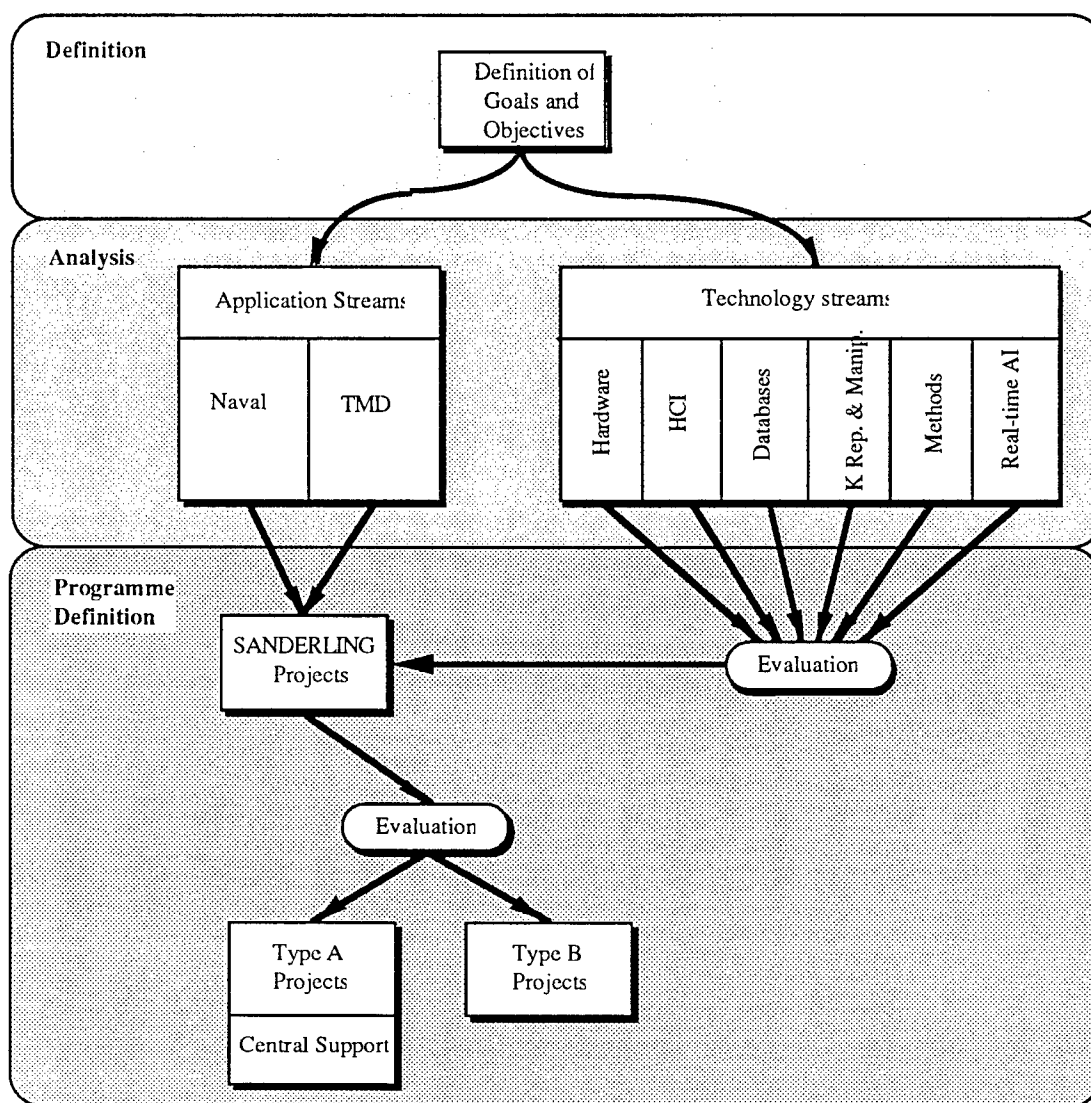


Figure 2.1

From the overall aim of the programme and an analysis of research goals, a hierarchy of objectives at three levels was derived. Analysis included an assessment of the state-of-the-art in the relevant fields and technology streams, with an emphasis on the level of appropriate research activity in the UK.

The evaluation process was applied to the proposed projects and to the underlying technologies. The aims of evaluating the technologies were two-fold : to eliminate those which were peripheral to the main research thrust, and to give an early indication of the priorities which should be given to projects on the basis of their technical components.

The evaluation of the projects themselves was based on an assessment of :

- critical importance to the programme objectives;
- technical risk / timescales;
- compatibility with existing ARE programmes;
- availability of UK expertise.

The final programme defines a set of high priority research projects (Type A), the total cost of which is within the £7M budget limit, and a second set of lower priority projects (Type B), taking the total up to twice the budget. The programme also contains an outline plan, which includes a provision for adequate central support facilities, estimates of time and effort, timetables and dependency details.

### 3. DEFINITION AND ANALYSIS

The Definition stage generated a number of goals for the research programme, the top-level objectives and a set of eight research streams for further investigation. The Analysis stage identified principal sub-topics within each research stream and assessed the relevance and importance of each sub-topic to the objectives of the research programme.

#### 3.1 Goals

The stated aim of the programme is "The execution of a vigorous research programme to explore various opportunities to exploit the advantages knowledge based systems techniques can provide in dynamic and complex defensive operations".

To complement this aim and to help define objectives for the research programme, a number of technical goals were postulated about the:

- function of systems to be developed;
- performance they must fulfil;
- users they must support;
- systems environment in which they will work;
- special operational requirements.

The goals for the Naval and SDI components were somewhat different. In the former there is a large corpus of existing work that has led to viable techniques for elements in of the C<sup>2</sup> problem, and an existing infrastructure into which new systems must fit. In the latter, work takes place on a "greenfield site", there are few constraints imposed by existing systems and methods. However, many of these goals are common to both Naval and TMD requirements, for example those relating to situation assessment and the development of verification and validation techniques.

##### 3.1.1 Naval Programme Goals

Naval C<sup>2</sup> was functionally decomposed into the processes of:

- Data Fusion;
- Situation Assessment;
- Resource Allocation;
- Planning.

Improvements to the level of automation in these functions should be the primary goals of the research effort but important subsidiary goals should also include: performance, users, the systems environment and operational concerns.

Performance requirements are driven by system interfaces such as the incoming data rate and the speed needs of the operator. These performance requirements will shape the research that needs to be done on implementation methods, particularly processing power requirements and real-time architecture considerations. However, they will also impact on the quality and type of information that can be made available to the user. Also, there is a need to have mechanisms for identifying and measuring these parameters and designs that meet the demands placed on the system.

### 3.1.2 SDI Programme Goals

The main assumption has been that the primary interest and scenario driver for this work is Theatre Missile rather than Strategic Missile Defence. Thus, the main input to the study has been from UK generated TMD documents. However, because of the limitation of these documents and their associated scenarios in the wider context, the study has also taken some note, where information has been available, of Strategic Defence (SD) issues.

The BMC<sup>3</sup> study has already gone some way into performing a top-down examination of the functional requirements stemming from the UK Architecture Study. Six top-level functions are identified:

- compile surveillance picture;
- command BMC<sup>2</sup> system;
- evaluate situation;
- decide action;
- manage BMC<sup>2</sup> sub-systems;
- direct sensors and weapons.

Unlike the Naval domain, these processes are expected to be largely automatic, at least in the TMD context. In the SD context a high degree of man-in-the-loop is required.

Areas already identified for research are track correlation, object discrimination and impact prediction.

The TMD scenarios postulate many times the number of objects in the sensor picture that exist in the Naval case. There are expected to be up to 80,000 independent objects (including decoys) identifiable in the field of view. A scenario is expected to evolve over a period as short as 400 seconds. Given these approximate figures we could expect a processing demand four to five orders of magnitude greater than for the naval scenarios, at least at the Data Fusion level.

However, the relative magnitude of processing required diminishes at the higher function levels, since the tactical complexities of the TMD scenario are likely to be less than those pertaining in Naval warfare. We might expect two orders of magnitude more processing at the Situation Assessment level, due to greater numbers, and similar or better at the resource allocation level.

Despite the anticipation of largely autonomous functioning of the TMD system it is inevitable that there will be users of the system who must assess the conclusions of its analysis and sanction responses. It is unlikely that a user would supplement or intervene in much of the low-level decision making since it is too time-critical. The requirement therefore is for rapid and accurate situation display and high level, high speed, decision support.

The architecture studies into TMD have proposed a three tier system that decision support aids will have to operate within: Sector, Regional and Theatre. The functions to be performed within this architecture mean that there will be considerable data transfer between nodes, since both data and commands are moving between hierarchy levels. The tolerance of the network to loss of nodes is of considerable importance within the system architecture considerations. Each node is to have a high degree of autonomy and the co-ordination of functions across the network is therefore worthy of study.

### **3.2 Research Streams**

The Definition activity identified a large number of issues which needed to be covered by the research programme. These are logically grouped into eight research streams, six addressing technical issues and two concentrating on the requirements of the Naval and TMD application areas.

#### **3.2.1 Streams and Sub-topics**

The six streams addressing technical issues were :

- Hardware Architectures;
- Human-Computer Interaction;
- Database / Knowledgebase Interaction;
- Development Methods;
- Knowledge Representation & Manipulation;
- Real-Time Systems Design & Distributed Artificial Intelligence.

The remaining two streams were concerned with the application domains, and serve to guide and focus the results from the other streams. The Application Streams are:

- Naval Applications;
- TMD Applications.

### 3.2.2 Analysis and Evaluation of Sub-topics

The structure and scope of the technology streams were analysed primarily in terms of a set of sub-topics for each stream. These were derived from studies into the state-of-the-art in each stream, directed by the findings of the application streams on the operational requirements of Naval and TMD C<sup>2</sup> systems. The sub-topics identified for each stream were:

Research Stream	Sub-topics
1. Hardware Architectures	Paradigms Hardware Tools Neural Nets
2. Systems Design	Real Time / Systems Distributed AI
3. Knowledge Representation and Manipulation	Reasoning about uncertainty Planning Situating Action Spatial reasoning Temporal Reasoning Agent Modelling Reason Maintenance Systems
4. HCI	Design methods & tools User support Modelling issues Cognitive issues Organisational issues Physical interface
5. Database / Knowledge Bases	Coupling Dynamic databases Intelligent front ends Novel databases AI-enhanced databases KBMS
6. Development Methods	Verification & Validation KB Maintenance Robust architectures Formal specification Life cycle models Knowledge acquisition Development tools Machine Learning

The research sub-topics within each technology stream were evaluated to assess their suitability for inclusion in the research programme.



### **Hardware Architectures**

The results of the evaluation of sub-topics within the Hardware Architectures Stream indicated that priority should be given to the sub-topic of Paradigms. This was based on the following assumptions :

- the performance required for the Naval system may or may not require a parallel hardware solution, but TMD systems almost certainly will;
- if a parallel solution is required, the emphasis in the research programme should be on the definition of suitable paradigms;
- the requirement for tools reflects the need to implement paradigms;
- some technology tracking of hardware options will be required, regardless of the type of option selected (parallel v. conventional);
- Neural networks are clearly relevant, but cannot be seen as critical at this stage.

### **Systems Design / Knowledge Representation**

The results of the evaluation of sub-topics within the Real-Time Systems and Knowledge Representation & Manipulation Streams suggested that it was difficult to separate the knowledge representation sub-topics for evaluation. However, reasoning about uncertainty and temporal elements were high priority, particularly in the contexts of enhancing the functionality of Naval and TMD applications. Real-time systems engineering was given high priority for TDS deployment. These conclusions were based on the following assumptions :

- the current TDS is based on a single-chip architecture, and it would be inappropriate to re-design it as a distributed system for operational deployment;
- real-time systems engineering will be critical to the operational deployment of the naval system, but relatively little further research may be needed for its application to enhanced systems and TMD systems;
- the knowledge-base architecture of the TDS has been defined and it would be inappropriate to re-design it using alternative knowledge representation schemes;
- planning is concerned entirely with enhanced functionality and has no relevance to operational deployment of the current TDS.

### **Human Computer Interaction**

The results of the evaluation of sub-topics within the Human Computer Interaction Stream indicated that the sub-topics of Design Methods, User Support and Modelling issues were of particular importance for TDS deployment, but that research into physical interfaces was a high priority for enhancing the functionality of C<sup>2</sup> systems.

These conclusions were based on the following assumptions :

- the physical interface for the current TDS is already well developed, and further research would not be critical to its operational deployment;
- modelling issues are seen as the most critical to the programme in the longer term, and are the area in which HCI research can probably make the most important contributions.

### **Database/Knowledge Base Interaction**

The results of the evaluation of sub-topics within the Database/Knowledge Base Interaction Stream were significantly different for the Naval and TMD objectives. The coupling of databases and knowledge bases was the highest priority sub-topic for TDS deployment and enhanced functionality of Naval systems, but Dynamic Databases were of greater importance in the context of TMD applications. These conclusions were based on the following assumptions :

- the direct coupling of existing database and knowledge base components is the most pragmatic approach in the short term, and therefore the most appropriate for the operational deployment of the TDS. In the longer term it will probably be overtaken by developments in novel databases;
- research into the design of dynamic databases will be critical to all C<sup>2</sup> systems, but of particular importance in the TMD context.

### **Development Methods**

The results of the evaluation of sub-topics within the Development Methods Stream confirmed the importance of the Verification and Validation sub-topic. KBS Maintenance was also given a high priority. These conclusions were based on the following assumptions :

- the problem of specifying knowledge based systems is of key importance to the procurement process and is therefore of paramount importance in the research programme;
- KBS development tools are not seen as critical to any of the objectives, and currently available tools may suffice;
- machine learning is clearly relevant to the programme but cannot be regarded as critical at this stage.

#### **3.2.3 Balance and priorities between streams and sub-topics**

Having identified the priorities within each research stream, the study considered the desired distribution of research effort across the streams. The results of the evaluation of streams and sub-topics were combined with the feedback received from the ARE and the SDIO. This represented input to the process of generating and evaluating the final set of SANDERLING projects, but did not imply that the recommended programme should contain exactly the same technology balance.

The resulting balance between streams and sub-topics is summarised below :

Research Stream	Priority
1. Hardware Architectures (paradigms are the priority)	Low
2. Real-time and systems (system engineering and distributed AI are the priority)	Low
3. Knowledge Representation and Manipulation (uncertainty, temporal reasoning and planning are the priorities)	High
4. Human-Computer Interaction (HCI) (physical interface, user support and design methods and tools are priorities)	Medium
5. Database/Knowledge Base Interaction (dynamic databases and coupling are priorities)	Low
6. Development Methods (validation and verification, machine learning, specification and maintenance are priorities)	Medium

## **4. THE RESEARCH PROGRAMME**

### **4.1 Strategy**

The strategy for deriving the research programme is based on a review of the programme objectives and assumptions. These are then developed into a framework for the research programme and a discussion on the balance of projects across a number of dimensions. The programme is then divided into four categories of research projects.

#### **4.1.1 Objectives**

Objectives have been grouped into a hierarchy of three levels:

- Level One : The major objectives of the programme;
- Level Two : The technical objectives that support each top-level objective;
- Level Three : The specific research objectives to be achieved by individual projects or groups of projects.

Level One :

- Deployment Capability: To advance the capability to deploy naval KBS based C<sup>2</sup> systems at sea;
- Enhanced Functionality: To extend the functionality of current KBS based C<sup>2</sup> demonstrator systems;
- TMD Requirements: To provide the basis on which to deploy and deliver KBS based solutions to functional requirements for TMD C<sup>2</sup> systems.

The first objective is primarily focussed on the engineering, performance and development issues associated with moving the current technology out into operational systems at the earliest date.

The second objective accepts that the capability of current technology to provide the full range of future functional requirements will be limited and that work is necessary to investigate and explore more advanced ideas and to incorporate these into future demonstrators.

The third objective incorporates the first two objectives above, but concentrates specifically on the TMD domain.

## Level Two :

## Deployment Capability :

- To provide practical support to the TDS trials deployment via: training and assistance in the experimental use of the TDS; modifications for performance optimization; evaluation and assessment of TDS capability; data collection, processing and analysis;
- To extrapolate TDS experience to operational system deployment by examining the feasibility of scale and performance extensions to meet future operational requirements;
- To make use of the TDS deployment to achieve objectives such as: define KBS development methods; establish metrics for assessing system performance; assess the level of user/organisational impact; refine the user requirements for advanced C<sup>2</sup> systems; determine the feasibility of the TDS design and systems architecture; define a growth/development path for the TDS.

## Enhanced Functionality :

- To extend, via prototypes, the functional support provided by KBS further into non-data fusion areas such as situation assessment, resource allocation and planning;
- To investigate and discover new techniques for knowledge representation and manipulation in the domains of situation assessment, resource allocation and planning;
- To establish the feasibility and benefits of parallel architectures for functions such as data fusion;
- To establish an outline architecture for an integrated battle management prototype;
- To investigate novel/non-KBS areas of significant potential advantage such as distributed AI, machine learning and neural networks.

## TMD Requirements :

- To explore and define development techniques in critical aspects such as: verification, validation, specification and maintenance; performance limitations and improvements; and the significance of Human Computer Interaction (HCI) issues;
- To extend, via prototypes, the functional support provided by KBS further into aspects of situation assessment, resource allocation and planning which are specific to TMD;
- To investigate and discover new techniques for knowledge representation and manipulation in the TMD domain;

- To identify paradigms which offer tractable solutions to the scale of the signal processing problem;
- To establish an outline architecture for an integrated TMD battle management prototype;
- To investigate novel areas of significant potential advantage such as machine learning and neural networks.

#### **4.1.2 Assumptions**

##### **4.1.2.1 Time Horizons**

The research programme will be aimed at generating results that can be used operationally over a time horizon extending beyond the three year period of the programme itself. The timing assumptions used are based on supporting a standard procurement life cycle. They are generally longer for addressing the TMD objectives since the Naval objectives place more emphasis on supporting trials and deployment in a shorter timescale than is appropriate for TMD/SDI.

##### **4.1.2.2 TMD Scenarios**

The research projects and programme have been based primarily on the the United Kingdom Architecture Studies (UKAS) and the Battle Management Command, Control and Communications (BMC<sup>3</sup>) Studies. However, this study has also taken into account wider Continental US (CONUS) issues as reflected in the Strategic Defense Systems (SDS) Phase 1 System Description Document F144-23-2.

##### **4.1.2.3 Relationship to ARE Programme and Plans.**

We have endeavoured to include in our list of projects those elements of ARE plans that are not yet underway and that ARE have indicated were a priority.

##### **4.1.2.4 Cost / effort**

Estimates of effort in man years are based on an analysis of each individual project and on the assumption that the work would be carried out by skilled and competent research staff. Where appropriate we have indicated the expertise required to perform a given project. This applies particularly to projects which have been short-listed for the research programme.

An average figure of £80K per annum per person has been used for external industrial support or ARE staff. A figure of £40K per annum per person has been used for university staff. Hardware, software and other material costs are indicated where appropriate or the assumptions for their exclusion are stated.

The estimates are approximate and for budgetary purposes only. The effect of inflation has not been included in the present costings. Neither has an allowance for expenses been included in the cost estimates.

#### 4.1.3 Key Aspects

In defining the research programme, particular emphasis has been given to the following key aspects :

- Special and critical issues

Projects included in the programme must concentrate strongly on special aspects and critical gaps in the technology. This is driven by the size of the budget, which is not large compared to the size of a single large ESPRIT (European Special Programme for Research in IT) project in KBS.

- Maximum linkage to other programmes

The greatest possible use must be made of the existing and planned research programmes at ARE and at other establishments such as RAE and RSRE. This will avoid duplication, make the most of lessons learnt already and will reinforce the work in those related areas.

- Strong support for the TDS

The success of the TDS is crucial for KBS supported Naval Data Fusion and further C<sup>2</sup> functions. There must therefore be a strong emphasis in the programme on supporting and enhancing the use of the TDS demonstrator.

- Build two major TMD prototypes

An early prototype in the TMD domain is essential to provide a means of carrying out other research into development techniques, (eg verification and validation) and as an example of KBS supported functionality in SDI. This Development Methods Prototype should be commenced at the beginning of the programme and should complement other SDIO work in the UK. In addition, one other major prototyping project should be undertaken in the SDI/TMD domain as the basis for investigating a number of advanced issues.

- Explore advanced capability

Research projects must look beyond the current generation of TDS work and provide a basis for more advanced capability.

- Practical demonstration of the technology

Research should concentrate on experimental projects that test and demonstrate the practical application of the technology. There should therefore be an emphasis on projects which generate prototypes. There will be limited opportunity and funding for state-of-the-art-surveys, but projects that include new theoretical studies can be included.

- Plans for an advanced Battle Management and C<sup>2</sup> demonstrator (BMC<sup>2</sup>D)

The technology embedded in the TDS can be extended to include higher levels of functionality than Data Fusion in the naval context. However, this capability is limited and could restrict future requirements to use new and later research results, especially in the SDI/TMD domain. There is also other work in the UK on TMD which will need to be integrated with the SANDERLING research projects. The programme should therefore include the concept of an advanced Battle Management and C<sup>2</sup> demonstrator (BMC<sup>2</sup>D). This will provide a focus for many aspects of the research programme and will define the way forward in knowledge-based C<sup>2</sup> systems. During the programme an outline specification of the demonstrator should be undertaken.

- Joint programme

This is a joint research programme and it is therefore important that there is maximum synergy between Naval and TMD themes and a roughly equal balance of resource between them in the programme. The range of projects should include those that jointly benefit both domains (eg KBS development methods) and some that are more specifically focussed on naval or TMD needs (eg direct support to the TDS). Most projects will produce benefits for both domains.

- Programme management

There is a planned budget of £7M and approximately 20 projects with a range of tightly defined objectives. It is essential for success that adequate provision is made to manage and evaluate the programme efficiently.

#### **4.1.4 Overall Framework**

The overall framework of the research programme and its relationship to current and planned activities is set out in section 4.1.5. Projects will fall into three major categories:

- Applied Research;
- Enabling Research;
- Central Support.

##### **4.1.4.1 Applied Research**

This will absorb approximately 70% of the resource and will be primarily related to existing and planned work associated with:

- deploying the TDS in an integrated C<sup>2</sup> system;
- building and using two TMD related prototypes;
- enhancing the naval laboratory demonstrators and prototypes.



It is envisaged that research projects in this area will be strongly driven by the functional/application themes identified from UKAS/BMC<sup>3</sup> studies and naval operational requirements. It will also be closely coupled to the current ARE planned research. Individual research projects will be strongly linked to these functional research themes. All projects in this category will address measurable short-term objectives and will produce relevant deliverables within the timescale of the three year programme.

#### 4.1.4.2 Enabling Research

This will absorb approximately 20% of the resource and will be related to enhanced functionality in the longer term and new demonstrators such as the definition of an advanced Battle Management Command and Control Demonstrator (BMC<sup>2</sup>D). It is envisaged that projects in this area will be of significant relevance to a future BMC<sup>2</sup>D but that they will not necessarily be directly linked to a functional theme such as situation assessment. They could, for example, be relatively small and exploratory stand-alone projects. Projects of longer term interest will be included as long as they have potential application relevance and can otherwise be justified.

#### 4.1.4.3 Central Support

Advice from those who have been involved in managing other large research programmes suggests that the allocation to these central support projects should be about 10% of total budget.

#### 4.1.4.4 Balance

Emphasis should be placed upon the applied end of the spectrum rather than longer term enabling research. There are two main arguments for this; firstly a good deal of earlier ARE exploratory work is now ready to be engineered for practical evaluation and making sure that this happens effectively is crucial for continuing support of the technology; secondly, the limits of what can be done with existing techniques need to be fully investigated and clearly understood.

However, it is appreciated that to achieve significant strides in functional improvement, radical new approaches will be needed. It is therefore essential that a balance is maintained, with a significant amount of resource allocated to enabling research. This will ensure continuity and development of C<sup>2</sup> capabilities beyond the time horizon of the current demonstrators.

#### 4.1.5 Categorisation of SANDERLING projects

Within the principles outlined above, the proposed SANDERLING projects (SP) are categorised as follows, in terms of the needs of the Naval and TMD domains :

Cat	Description	Primary Domain	Sub-category
1.	TDS Support	1.Naval	1. TDS Support
2.	Applied Research	1.Naval	1. TDP 2. Lab/TDS Enhance 3. Use Lab Demo 4. Stand-alone Prototypes
		2.TMD	1. Lab Enhance 2. Use Lab Prototypes 3. Stand-alone Prototypes
3.	Enabling Research	1.TMD & Naval	1. Adv Prototypes 2. Tech Projects
4.	Central Support	1.TMD & Naval	1. Projects

The sub-categories are defined as follows:

- Cat 1.1.1 TDS Support. This covers work that is in direct short term support of the sea going trials of the TDS.
- Cat 2.1.1 TDP (Technology Demonstrator Programme). This category of projects provides indirect support to the TDS.
- Cat 2.1.2 Lab/TDS Enhance. This covers projects that develop and enhance the TDS or other prototypes already under development.
- Cat 2.1.3 Use Lab Demo. This category includes projects that specifically make use of prototypes and demonstrators to carry out experiments.
- Cat 2.1.4 Stand-alone Prototypes. These are projects that involve the creation of new prototypes that are not directly integrated with other existing or planned demos or prototypes.
- Cat 2.2.1 Lab Enhance. This covered projects that develop and enhance the TMDD (TMD Demonstrator). The category is no longer appropriate and detail on projects in this category is not included.
- Cat 2.2.2 Use Lab Prototypes. This category previously covered projects that specifically made use of the TMDD to carry out experiments. They will now be based on a Development Methods Prototype defined under Cat 2.2.3

Cat 2.2.3 Stand-alone Prototypes. These are projects that involve the creation of prototypes that are not directly integrated with a major demonstrator. This will include the Development Methods Prototype.

Cat 3.1.1 Advanced Prototypes. These are enabling research projects that specifically aim at the generation of new prototypes in both Naval and TMD domains.

Cat 3.1.2 Technology Projects. This category includes all other longer term enabling research not included in 3.1.1.

Cat 4.1.1 Central Support Projects. These are projects that span a number of other areas and provide support or long term focus for the programme.

## 4.2 Research Projects and Programme

### 4.2.1 Projects

The proposed research projects are summarised below. Further details, including estimates of cost and effort, are given in Annex ES1.

#### 4.2.1.1 Category 1 : TDS Support

The objectives of the SANDERLING projects in Category 1 are to provide short-term support to the TDS installation which will shortly be undergoing trials at sea.

The research issues to be addressed are as follows:

- to investigate the feasibility of enhancing the TDS to cope with more complex scenarios;
- to investigate techniques for optimising rule-based KBS for performance and demonstrating their effectiveness using the TDS;
- to investigate the development of training material for the users of knowledge based command and control systems, using the TDS as an examples.

The projects included within Category 1 are as follows:

**SP 1.1.1 Investigate the operational scalability of the TDS :** This project will determine the operational scalability of the existing solution to the data fusion problem.

**SP 1.1.2 Enhance TDS Performance by Knowledge Base Optimisation:** This project will increase the operating speed of the TDS Version 1 Phase 3 by focussing attention on the efficiency of the KBS implementation.

**SP 1.1.3 Development of Training for the TDS :** The objectives of this project are: to produce comprehensive training material for prospective users and operators of the TDS Version 1 Phase 3, to run training courses at ARE, and to evaluate and improve the quality of the training material to resolve and anticipate user and operator problems recorded during the sea trials.

#### 4.2.1.2 Category 2.1 : Applied Research (Naval) Projects

The objectives of the research proposed within Category 2.1 fall into three main areas:

- to evaluate and assess the performance of the existing TDS;
- to develop techniques and tools to support the continued operation of the existing TDS;
- to enhance the functionality of the TDS by focussed research in a number of key technical areas.

The projects included within Category 2.1 are as follows:

**SP 2.1.1.1 Database/Kbase Interfacing Techniques for Applications to the TDS :** This project is concerned with establishing the most efficient techniques for coupling databases and KBS.

**SP 2.1.1.2 KBS Performance and Competence Metrics for the TDS Evaluation Programme :** The generation and evaluation of a set of performance and competence metrics for the TDS, for use in the evaluation of the trials' results and in subsequent projects on KBS evaluation.

**SP 2.1.1.3 Evaluation of the operational impact of the TDS :** This project will assess the impact of the TDS on the operational infrastructure within which it is installed.

**SP 2.1.1.4 Methods and Tools for Task Analysis :** The generation of tools and methods for the analysis of human and computer task boundaries and interfaces.

**SP 2.1.1.5 Optimise HCI Design :** This project is concerned with optimising the design of the TDS interface. It includes consideration of display paradigms, and dialogue styles etc.

**SP 2.1.1.6 Operator Interaction :** An analysis of the interaction of an operator with the TDS. It will consider the effects on performance of the TDS system as a whole and will identify potential knowledge based enhancements and human contributions to the data fusion process.

**SP 2.1.1.7 Validation of the TDS HCI :** The HCI of the TDS needs to be assessed at three levels: presentation, information level and operator understanding. The project is aimed at meeting these objectives.

**SP 2.1.1.8 To Evaluate the TDS as a Data Fusion System :** This project will evaluate the TDS as an interactive data fusion system, performing in an operational environment.

**SP 2.1.2.1 Enhanced Situation Assessment Prototype :** The project extends the Situation Assessment prototype currently being procured to support its use in an operational context more directly and to rationalise the representation schemes as a basis for further work in resource allocation and planning.

**SP 2.1.2.2 Enhanced Resource Allocation Prototype :** This project enhances the Resource Allocation Prototypes to support their continued development as decision support tools and the refinement and rationalisation of their internal workings.

**SP 2.1.2.3 Enhanced TDS Performance by Concurrent Processing :** This project will continue the work done to date at ARE on examining the potential for exploiting concurrent processing within the TDS Version 1.

**SP 2.1.2.4 HCI for Situation Assessment and Resource Allocation :** This project will investigate the processes underlying human situation assessment and resource allocation and produce a validated model that will be suitable for determining how best to provide computer based assistance and HCI facilities for the situation assessment and resource allocation functions.

**SP 2.1.3.1 Development of Techniques for KBS Maintenance :** This project will investigate extensions to the KBS life cycle model and will develop prototype software tools to support the maintenance of knowledge based systems for C<sup>2</sup>.

**SP 2.1.3.2 Investigation of techniques for Knowledge Acquisition :** In order to support the development of future enhancements of the TDS there will be a need to carry out knowledge acquisition in domains with a temporal or a spatial component.

**SP 2.1.3.3 Development of Methods and Tools for the A Posteriori Validation of KBS:** This project is concerned with the development and assessment of techniques for the *a posteriori* validation of real-time KBS, using the TDS Version 1 knowledge base as a testbed. (*A posteriori* validation refers to validation which is carried out after the system development process has been completed.)

**SP 2.1.3.4 Exploration of Techniques for Explanation in Situation Assessment Systems :** This project will extend the work done to date at ARE on the development of a graphical explanation facility for the data fusion module of the TDS, specifically to produce explanation facilities for use with the situation assessment module of the TDS.

**SP 2.1.4.1 Exploration of Adaptive Interfaces for C<sup>2</sup> systems :** This project will investigate the opportunities for the design and prototype implementation of a KBS to facilitate and improve the quality of the HCI component of the TDS system.

**SP 2.1.4.2 KBS Planners for Resource Allocation in Naval C<sup>2</sup> :** This project will develop an integrated system of co-operating KBS planners which assist the amphibious command in preparing ship stowage and disembarkation plans.

#### 4.2.1.3 Category 2.2 : Applied Research (TMD) Projects

Stand alone prototypes will be used to investigate TMD application functions. The objective of this line of research is to extend the work beyond data fusion into the more stressing (from an AI perspective) areas of TMD C<sup>2</sup>. Specific application-driven prototypes will act as vehicles for technology research.

A further class of objectives is aimed at utilising the application prototypes to investigate the use of supporting software methods in the development of AI-based systems.

The research issues addressed in the TMD projects cover three different but related aspects:

- The continual stretching of the boundaries of AI support to the functions in an SDI/TMD BMC<sup>2</sup> system;
- The integration of complementary technologies. It is recognised that for the long term optimal solution to the support of the BMC<sup>2</sup> function, the implementation will be by a hybrid of algorithmic, AI, novel and conventional information systems approaches;
- The TMD applications must be able to perform successfully in highly constrained and stressed situations. This implies the capability for a high level of autonomous action. However, practical and political considerations dictate that the man must retain a degree of control of the machine and the situation. For these reasons, there will be some requirement for a consideration of HCI issues.

The research projects within the TMD environment are divided into three categories :

- Category 2.2.1: projects that use the TMDD Phase 1 as a host. The projects in this category were planned to use the TMD Demonstrator as a host. However, because of the decision not to proceed with the TMDD these projects have now been withdrawn;
- Category 2.2.2: projects that use TMD prototypes to investigate supporting development methods. This category now includes provision for two new TMD prototypes as vehicles for research into methodology issues;
- Category 2.2.3: projects that extend the horizon of the use of AI techniques to functions for which it is best to perform the research on stand alone prototypes.

**SP 2.2.2.1 The Specification of KBS for Command and Control Applications :** This project will investigate the specification of a real-time KBS in the C<sup>2</sup> domain, by using the Development Methods Prototype (SP 2.2.3.4) as a test vehicle.

**SP 2.2.2.2 Verification and Validation of 'Safety Critical' KBS :** This project will investigate techniques for the *a priori* validation of C<sup>2</sup> applications of KBS and explore their effectiveness in relation to the Development Methods Prototype (SP 2.2.3.4). (The term *a priori* validation is used to refer to validation which is specifically integrated into the design and development process of the KBS.)

**SP 2.2.2.3 Investigation into the Robustness of KBS architectures :** This project will explore the robustness of the KBS Architecture of the Development Methods Prototype (SP 2.2.3.4) and recommend the best means of providing robust KBS.

**SP 2.2.2.4 Operational Adaptivity of Knowledge Bases :** The objective of this project is to investigate the adaptability of an operationally deployed system to changes "in the field". The research will investigate the feasibility of using machine learning techniques to enable in situ maintenance of KBS.

**SP 2.2.2.5 Integrating Knowledge Representation :** The aim of this project is to provide a well-founded set of knowledge representation formalisms drawn from the results of the studies and prototyping exercises taking place during the programme.

**SP 2.2.2.6 Development of KBS not based on 'Expert' Knowledge :** The objective of this project is to devise techniques which could be used for knowledge acquisition and validation in such application domains.

**SP 2.2.2.7 Real-Time Integrated Databases :** This experiment is an investigation of issues in integrating databases with knowledge bases for TMD applications.

**SP 2.2.3.1 Adaptive Preferential Defence :** The object of the experiment is to investigate and show the use of HCI and AI techniques, working together, in the time-constrained resource allocation application.

**SP 2.2.3.2 Sensor Management :** The object of this project is to show the use of HCI and AI techniques, working together, in an application which is driven by spatial representation and display.

**SP 2.2.3.3 Intention Prediction of Intelligently Manoeuvring Objects :** The object of the experiment is to show how AI techniques can be used to forward predict the track of objects with known pre-programmed manoeuvre capability.

**SP 2.2.3.4 Development Methods Prototype :** The main objective of the project is to provide a focussed applications prototype to support the investigation of techniques for the specification and evaluation of KBS outlined in the Category 2.2.2 projects list.

**SP 2.2.3.5 Hybrid Approach to Data Fusion :** The overall goal of this research is to determine the most promising paradigms for integrating symbolic and numeric techniques of data fusion, and to evaluate their likely performance in comparison to a fully AI or numeric based solution.

#### 4.2.1.3 Category 3 : Enabling Research Projects

##### Category 3.1.1 Enabling Research (Applications) Projects

This category of projects look further forward than the application led projects in Category 2 are able. The projects in this category address issues raised in both application domains.

The main research issues are:

- the use of knowledge based decision support systems on multiple ships, and their co-ordination;
- casting the decision support system's role as a tool for man-based decision processes, i.e. addressing aspects of "man-in-the-loop" operation as opposed to "man in supervisory control".

**SP 3.1.1.1 Distributed Situation Assessment** : The aim in this project is to examine the practical constraints on the distribution of information and functions within a Naval task force or TMD command structure and to examine the best means of co-ordinating Situation Assessment between a number of platforms.

**SP 3.1.1.2 Co-operative Planning Aids for C2** : This project will investigate planning as a joint human/machine process of exploration and elaboration of plans.

##### Category 3.1.2 Enabling Research (Technology) Projects

This category covers topics that are felt to be of relevance and importance but which are best tackled by specific technology led projects.

**SP 3.1.2.1 The Application Of Neural Networks to Data Fusion** : To study alternative inherently parallel knowledge representation models, specifically Neural Networks, in order to discover whether it is feasible to map the data fusion domain onto these models.

**SP 3.1.2.2 The Application of Machine Learning to Data Fusion** : To apply the process of Machine Learning initially to a Data Fusion Knowledge Base and thereby seek to improve its efficiency, refine its rule base and enhance its ability to acquire new kinds of knowledge.

**SP 3.1.2.3 Application of Formal Methods in the Development of KBS** : This project continues work to assess and use the applicability of techniques for converting formal representations of software into executable code and to assess the practicality of using them.

**SP 3.1.2.4 Intelligent Training Facilities for C2 Systems** : This project examines the development of embedded intelligent training facilities within the on-ship systems that will interactively exercise operators for initial and in-service familiarisation with the system's capabilities.



**SP 3.1.2.5 Genetic Algorithms for C2 Systems** : This project is aimed at small-scale experiments in applying GAs to aspects of Command and Control problems for an assessment of their relevance and future impact.

**SP 3.1.2.6 Machine Learning of Temporal Patterns for Command and Control** : This project explores representation of temporal structure of events with grammars and automatic acquisition of grammars from scenario data.

#### 4.2.1.5 Category 4: Central Support Projects

In formulating the research projects it was recognised that there were some activities associated with the research programme that did not conveniently fall into the other categories but would nonetheless be important in achieving overall success for the programme. The objectives of central support projects are to:

- support a range of both TMD and Naval projects;
- prepare the way ahead for work beyond that directly included in the 3 year research programme.

**SP 4.1.1.1 Specification of Advanced Battle Management Demonstrator** : The aim of this study is to lay the foundations of a future design and implementation project that would follow on at the end of the currently planned 3 year programme.

**SP 4.1.1.2 Scenario Generation and Data** : This project is intended to reserve some programme resource for this work without, at this stage, being too specific as to how this will be achieved for individual projects.

**SP 4.1.1.3 Provision of HCI Investigation/Trials Facilities** : Provision needs to be made for the allocation of such a resource to a number of projects.

**SP 4.1.1.4 TDS Facilities Management** : Many of the proposed projects plan to use the TDS. To provide use of these facilities will require a range of project tasks.

**SP 4.1.1.5 Programme Management** : This project is to ensure an allocation for such support is included in the programme.

**SP 4.1.1.6 Programme Evaluation** : The programme will require staff resource to provide support with the evaluation of the results and achievements of projects and the programme.

**SP 4.1.1.7 TDS Trials Data Processing** : This project makes provision for the processing and reduction of data recorded during trials of the TDS.

#### 4.2.2 Evaluation and Recommendations

##### 4.2.2.1 Evaluation Procedure

As required by the study, the complete set of research projects is estimated to cost approximately twice that of the planned budget of £7M. This section assists in the selection of projects and the definition of a recommended programme that is close to the planned budget.

The two primary criteria for evaluating projects are:

- Criticality : how critical is this project to the achievement of the objectives of the Research Programme?;
- Risk / timescales: how high are the technical risks incurred in attempting to achieve significant progress ? In most cases the risk will be associated with long research timescales.

Secondary criteria used are:

- Link projects: these are the projects on which other projects have strong dependencies, either providing an experimental platform or generating results which are required by the other projects. These dependencies are not listed in the evaluation tables, but are identified and discussed in the final Type A listings;
- Defined deliverables: the deliverables generated by the project. The priority is given to projects which have clearly defined short term deliverables, eg tools, prototypes;
- Special Research: the degree to which the research is unique to Naval/TMD C<sup>2</sup>. The priority is where the research is very specific to Naval/TMD C<sup>2</sup> and is very unlikely to be carried out elsewhere;
- Special Capability: the extent of UK expertise in the area. The priority is where the UK is known to have a special edge in a research field;
- Result / cost: The ratio of expected results to estimated cost. The priority is for projects that maximise the result / cost ratio - eg by building on existing work or utilising available hardware resource.

On the basis of section 4.1.4, the target Type A project budgetary allocation is:

Category	Budget (£'000)	%
1 TDS Deployment	350	5
2.1 Applied Research - Naval	2100	30
2.2 Applied Research - TMD	2450	35
3 Enabling Research	1400	20
4 Central Support	700	10
TOTAL	7000	100

The projects listed as Type A comprise the set of recommended projects costing up to the budget limit for each category. The Type B projects make up the remainder, costing an equivalent amount above the budgetary limit.

**Type A: Projects within the target budget**

**£'000**

Category 1 :

SP1.1.1 Investigate operational scalability of TDS	160
SP1.1.2 Enhance TDS performance by KB Optimisation	200
Total :	360

Category 2.1:

SP2.1.1.2 KBS Metrics	160
SP2.1.1.3 Evaluation of the operational impact of the TDS	120
SP2.1.1.7 Assessment of the MMI	240
SP2.1.1.8 Evaluation of the TDS as data fusion system	160
SP2.1.2.1 Enhance situation assessment prototype	560
SP2.1.2.4 HCI for situation assessment	480
SP2.1.3.1 Techniques for KBS maintenance	320
Total :	2040

Category 2.2 :

SP2.2.2.1 Specification of KBS	200
SP2.2.2.2 Verification and validation of KBS	480
SP2.2.2.7 Real-time integrated databases	240
SP2.2.3.2 Sensor management	680
SP2.2.3.4 Development methods prototype	320
SP2.2.3.5 Hybrid data fusion	400
Total :	2320

Category 3 :

SP3.1.1.1 Distributed situation assessment	400
SP3.1.1.2 Co-operative planning aids	440
SP3.1.2.1 Neural networks	180
SP3.1.2.2 Machine learning for data fusion	180
SP3.1.2.3 Formal methods	280
Total :	1480

Category 4 : 760

**Total Type A : 6960**

**Type B: Additional Projects within twice the target budget**

Category 1 :

SP1.1.3 Training for TDS	320
Total :	320

## Category 2.1 :

SP2.1.1.1 Database / knowledge base integration	160
SP2.1.1.4 Methods and Tools for task analysis	160
SP2.1.1.5 Optimise HCI design	200
SP2.1.1.6 Operator interaction	160
SP2.1.2.2 Enhance resource allocation prototype	400
SP2.1.2.3 Enhance TDS by concurrent processing	320
SP2.1.3.2 Techniques for knowledge acquisition	240
SP2.1.3.3 Validation of KBS	280
SP2.1.3.4 Techniques for explanation in KBS	160
SP2.1.4.1 KBS-enhanced HCI	120
SP2.1.4.2 KBS planners for resource allocation	360
Total :	2560

## Category 2.2 :

SP2.2.1.1 Evaluate and assess TMDD	240
SP2.2.1.2 Integrate data fusion	960
SP2.2.1.3 Incorporate SA and RA in TMDD	800
SP2.2.1.4 Integrate discrimination in TMDD	200
SP2.2.2.3 Robust architectures for KBS	160
SP2.2.2.4 Operational adaptivity of KBS	320
SP2.2.2.5 Integrating knowledge representations	180
SP2.2.2.6 Validation of 'non-expert' systems	80
SP2.2.3.1 Adaptive preferential defence	680
SP2.2.3.3 Intention predictor	560
Total :	4180

Category 3 :

SP3.1.2.4 Intelligent training systems 320

SP3.1.2.5 Genetic algorithms 180

SP3.1.2.6 Stochastic learning schemata 180

Total : 680

**Total Type B : 7740**

4.2.2.2 Rationale for Selection

Arguments based on the evaluation and supporting the division of projects into Type A and Type B are set out in detail in Part C of the Final Report. The principal points for each programme category are summarised below.

Category 1 : TDS Trials Support

All three projects in Category 1 are important to the TDS trials programme and the issues of KBS scalability (SP 1.1.1) and performance optimisation (SP 1.1.2) are also extremely relevant to the TMD programme. However, the development of training (SP 1.1.3) is largely a general support activity with a lower technical content, and must be seen as less relevant in the context of a research programme.

Category 2.1 : Applied Research, Naval

There are two link projects in this section, on which several other projects are dependent. The first is project SP 2.1.1.2, on the generation of KBS metrics. This project directly addresses one of the key objectives of the ARE programme, and will be of great importance to the TMD programme.

The second link project is SP 2.1.2.4 on HCI for Situation Assessment. This draws together many of the HCI issues (SP 2.1.1.4, SP 2.1.1.5 and SP 2.1.1.6), and explores them in the context of situation assessment. The project will address HCI problems which are of vital importance to both the Naval and TMD application areas. Other key areas of HCI research not covered by the link project are addressed in projects SP 2.1.1.3, SP 2.1.1.7 and SP 2.1.1.8, which are concerned with the broader assessment of the HCI requirements of C<sup>2</sup> systems. However, the more advanced concept of KBS Enhanced HCI (SP 2.1.4.1) must be regarded as lower priority in the context of the current programme.

Research into Database / Knowledge base interfacing (SP 2.1.1.1) has been excluded since it is not essential to the TDS trials programme, and the issues of real-time integrated Database / Knowledge bases for TMD applications are addressed by project SP 2.2.2.7.

Both the Enhanced SAP (SP 2.1.2.1) and Enhanced RAP (SP 2.1.2.2) are important to the objective of increasing the functionality of the TDS. However, the SAP is currently at a more advanced stage of development than the RAP, and could be used to explore and develop new knowledge representation schemas, which may subsequently be used in the enhancement of the RAP.

SP 2.1.3.1 is included because maintenance will become an increasingly important issue for operational knowledge based C<sup>2</sup> systems, in both the Naval and TMD domains. However, techniques for knowledge acquisition (SP 2.1.3.2) and Explanation (SP 2.1.3.4) are not considered critical at this stage, and should not be included in the research programme until some progress has been made in the knowledge representation projects themselves, such as SP 2.1.2.1 and SP 2.2.3.2. The *a posteriori* validation of KBS is excluded because this approach is already being investigated by ARE and for this reason the emphasis is placed on the *a priori* techniques of project SP 2.2.2.2.

Concurrent processing was originally identified as a potential research area, but pending the completion of project SP 1.1.1 on the scalability of the TDS, it is not yet clear whether a multi-processor architecture will be necessary to achieve the performance targets of the TDS. Concurrent processing is likely to be required for the TMD application, but is not critical to the next phase of the research programme. In view of the high level of general research activity in this area, it would be more appropriate to wait until the requirement has been better defined before including this project in the research programme.

Similarly in the area of KBS planners (SP 2.1.4.2), it is considered that the project may be superseded by general research in AI planning, and by the co-operative approach to planning which is explored in project SP 3.1.1.2.

#### Category 2.2 : Applied Research, TMD

There are two link projects in this section, both of which provide experimental platforms and an application focus for several of the methodology projects in the programme.

The first link project is concerned with Sensor Management (SP 2.2.3.2). The question of sensor management is critical to the TMD application and the research is special to the C<sup>2</sup> domain. This project complements project SP 2.1.2.4 on situation assessment, and redresses the lack of Type A projects on resource allocation in category 2.1.2. It also covers real-time design issues and meets the requirement for research in that technology. This project has been selected in preference to the other application projects, on Adaptive Preferential Defence (SP 2.2.3.1) and Intention Prediction (SP 2.2.3.3) since they are viewed as being longer term objectives, compared with the more immediate requirements for sensor management. Nevertheless, they are both concerned with issues which are special to C<sup>2</sup> systems and in view of the technical problems, should be included at an early stage in any subsequent programme.

All projects in Category 2.2.1 (Laboratory Enhancements to the TMDD), are currently excluded, in view of the uncertainty concerning the TMD Demonstrator.

The aim of the second link project, the Development Methods Prototype (SP 2.2.3.4), is to provide the experimental vehicle for the investigation of methodological issues in category 2.2.2, and replaces the TMDD in that role. At the same time, it will investigate a situation assessment application in the TMD domain.

This section of the programme addresses the key problem of KBS Specification (SP 2.2.2.1), and the related issue of Verification and Validation (SP 2.2.2.2). The problem of adequately specifying of knowledge based systems for the purposes of procurement and validation is generally recognised as one of the major obstacles to their operational deployment in both naval and TMD applications. The problems of verification and validation of KBS are related to the specification issue and research in this area will support project SP 2.2.2.1.

The Validation of KBS based on non-expert knowledge (SP 2.2.2.6) is not included at this stage, and the issues of operational adaptivity (SP 2.2.2.4) and robust architectures (SP 2.2.2.3) are already addressed to some extent by project SP 2.1.3.1 on KBS Maintenance.

Real-time Integrated Databases (SP 2.2.7) are included in this section because of their particular relevance to the TMD application. Research into Hybrid Approaches to Data Fusion is also included, since this approach must be seen as critical to any work in the TMD domain, where the scale and complexity of the scenarios dictate that algorithmic techniques must be integrated with AI to achieve the required performance and functionality. However, Integrated Knowledge Representation (SP 2.2.2.5) has been excluded, pending further research into the representation formalisms in application projects such as SP 2.1.2.1, SP 2.2.3.1 and SP 2.2.3.2.

### Category 3 : Enabling Research

The projects in the Enabling Research section represent the longer-term exploratory thrust of the research programme, and a number of important technical approaches are included.

Distributed Situation Assessment is included since it is likely that C<sup>2</sup> systems in both the Naval and TMD domains will need to have the capability to operate in distributed mode. The area is technically challenging and for this reason it is important that some research groundwork should be laid at this stage.

Planning systems are of particular importance to naval C<sup>2</sup>, but are also highly relevant to the TMD application, where there is a need for a dynamic replanning capability. The Co-operative Planning Aids project (SP 3.1.1.2) recognises the shortcomings of current AI planners and is a direct response to the expressed needs of operations staff. It combines AI and HCI issues and represents a more flexible and robust approach to the conventional techniques addressed in project SP 2.1.4.2.

Both Neural Nets (SP 3.1.2.1) and Machine Learning (SP 3.1.2.2) are included, since both techniques have a high potential pay-off for both Naval and TMD C<sup>2</sup> if they prove to be feasible. There is some UK capability in both areas on which to build, and both can be pursued as low-level exploratory research at university rates in the short term.



Formal Methods (SP 3.1.2.3) are also included because the UK has a particularly strong capability in this area, and there is a substantial body of research within ARE on which to build.

Excluded from this section are the projects on Genetic Algorithms (SP 3.1.2.5) and Stochastic Learning Schemata (SP 3.1.2.6). Both techniques are in an embryonic stage of research and at present there is insufficient evidence of their utility to justify their inclusion in the programme.

Intelligent Training Systems (SP 3.1.2.4) have also been excluded, since they are not critical to the deployment of the current TDS and must be regarded as lower priority in the short term, relative to other HCI problems.

#### Category 4 : Central Support

The central support activities will be required for any programme of research and are therefore included in the list of Type A projects.

### 4.2.3 Programme Plan

This section summarises information on effort, costs, dependencies and timings for SANDERLING projects, and presents an outline programme plan for Type A projects.

#### 4.2.3.1 Effort and Costs

The following summarise the key points on programme effort and costs:

- The total manning cost of all the proposed projects is £14,700K;
- The total manning cost of the Type A SANDERLING projects is £6,960K;
- The division of effort between Naval and TMD-related, Type A projects is 50.6% Naval and 49.4% TMD;
- The distribution of Type A projects reflects the input received from ARE and SDIO described in Section 3.2. Development Methods has a somewhat higher proportion of effort than originally expected.

#### 4.2.3.2 Dependencies

The scheduling of Type A projects into a programme has been based on an "earliest start strategy", where all projects are commenced at the earliest point possible, allowing for input dependencies. There are two main points arising from an analysis of dependency:

- Most SANDERLING projects are arranged as inter-dependent groups, for example:
  - SP 2.2.2.1 Specification, SP 2.2.2.2 Verification and Validation of Safety Critical KBS, and SP 2.2.3.4 Development Methods Prototype;
  - SP 2.2.3.2 Sensor Management, SP 2.2.3.5 Hybrid Approach to Data Fusion, and SP 2.2.3.7 Real-Time Integrated Databases.
- Three main critical paths have been identified:
  - SP 4.1.1.2 Scenario Generation;
  - SP 2.2.3.2 Sensor Management leading to SP 4.1.1.1 Specification of an Advanced Battle Management Prototype;
  - SP 2.2.3.4 Development Methods Prototype (together with the first phases of SP 2.2.2.1 and SP 2.2.2.2), which again leads to SP 4.1.1.1.

As well as the individual project dependencies outlined above, there are a number of projects which will share a common technology base. There will need to be a mechanism to ensure there is a good exchange of information between these projects.

#### 4.2.3.3 Timetable

An analysis of the timetable programme, taken to run from 1/7/90 to 13/7/93 raises the following points:

- the amount of slack available in projects which are running in the first half of the programme is minimal;
- some slack time has been allowed for in key external milestones i.e. The TDS Version 1 Phase 3, the SAP-0 and the commencement of sea trials;
- since there is slack time towards the end of the programme, this schedule (of Earliest Start) gives the research programme the best chance of finishing on time.

#### 4.2.3.4 Resource Profiles

In order to explore the alternative resource loadings for the programme, two alternative schedules were analysed. The Earliest Start (i.e. projects begin as soon as possible in the programme) and an "adjusted start" (i.e. project start dates are adjusted to give a more even resource profile across the programme) profile.

The main feature of the resource profiles resulting from these two schedules is the flatter profile for the Adjusted Start . This is desirable as it avoids the larger fluctuations in manning levels under the Earliest Start, and it also has the additional benefit of requiring less manpower in the first six months of the research programme. However, in spite of these characteristics, the earliest start schedule is recommended for the following reasons:

- The adjusted start schedule has the benefit of fewer people working on the programme in the first six months. This is offset by the fact that ARE already have at least 12 people who will continue to work on the research programme;
- The earliest start schedule offers far more slack time in the programme as a whole. Since we can expect there to be some slippage in a programme of this size, this is an important reason for selecting this option;
- If more people can be employed in the earlier stages of the programme this should be cheaper, assuming that the rise labour costing rates will be at least in line with inflation throughout the course of the programme.

## 5. RECOMMENDATIONS

As a result of the SANDERLING study there are a number of recommendations on the way forward. These are summarised as follows:

- Early action is needed to adopt and initiate the research programme;
- The recommended short list of selected projects should be used initially;
- Projects should be carried out as packaged groups of projects;
- A TMD 'Development Methods' package should be initiated early;
- The specification of a future BMC<sup>2</sup>D should be part of the programme;
- Adequate allowance should be made for management of the programme;
- A phased start to the programme would give an acceptable distribution of effort;
- Central projects such as scenario generation assessment should be started early.

It is recommended that early action should be taken to adopt and initiate the research programme. There are two main reasons for this recommendation. Firstly, the TDS programme requires immediate commencement. Secondly, allowing for contracting lead times the earliest date for projects to start is likely to be August 1990. Any later start begins to put pressure on the three year programme because of the firm end date in mid-1993.

To enable an early start we recommend that the proposed short list of selected projects (Type A) be used, at least initially. This list provides SDIO/ARE with an evaluated and reviewed set of priority projects.

There are 23 short listed Type A projects. Among many of them there is a degree of linkage and inter-dependency. We recommend that these projects be packaged into groups and that the packages are delegated to single industrial contractors or consortia. (eg scalability & optimisation; sensor management & database/KBS interfaces).

A set of projects that can be started initially are those that address the issue of development methods in the context of TMD/SDI. Projects on KBS specification, and verification and validation link closely to the development of a TMD prototype. The prototype will provide an early example of the use of KBS to support a TMD application and most importantly it will provide the application project which the development methods research can use.

The programme should include the concept of an advanced Battle Management and C<sup>2</sup> Demonstrator (BMC<sup>2</sup>D). This would provide a focus for many SANDERLING research projects and a clear way forward at the end of the programme. It would also provide a means of integrating other work in the UK on SDI/TMD battle management and C<sup>2</sup>.

There is a planned budget of £7M and approximately 20 projects with a range of tightly defined objectives. Although this will not be large in total value compared to national and international KBS research programmes, it is essential for success that adequate provision is made to manage and evaluate the programme efficiently.

The recommended scheduling for the programme is based on Type A projects commencing as soon as dependencies allow. The apparent 'cliff' in staff utilisation will be less severe than it appears. This approach will introduce more slack time into the programme, offering more flexibility for project management.

The programme includes a number of central support projects that will need to start at the beginning of the project. These will include programme management, which will need to draw up and instigate a management plan immediately.

## ANNEX ES1 : Table of Sanderling Projects

### 1. Category 1 - TDS Deployment

Serial No	Description	Type	ARE Nos	Technical topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
1.1.1	Investigate the operational scalability of the TDS	A	5.8	1.Hardware Archit. Paradigms 2.Dev Methods Robust Archit.	1.5y	2my	160	62
1.1.2	Enhance TDS Performance by KB Optimisation	A	12.1	1.Hardware Archit. Paradigms 2.Real-time Systems	1y	2.5my	200	57
1.1.3	Development of training for the TDS	B	7.1	HCI	3y	4my	320	45

#### Notes:

- Costs are expressed as a function of manning, each man year is costed at £80k. Resources have not been included.
- For further information on ARE Nos, see the ARE Research Programme Document AXT/23.01.02/90.
- As in Section 7, those man years of effort marked with an \* are costed at £60k each (the assumption being that the work would be shared between industry costed at £80k per man year and academia costed at £40k per man year).

**2. Category 2 - Applied Research****2.1 Naval****2.1.1 TDP Support**

Serial No	Description	Type	ARE Nos	Technical topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
2.1.1.1	Investigate database/KBase interfacing techniques	B	3.2,14.1	1.Database/KBase Coupling	1y	2my	160	55
2.1.1.2	Derive KBS performance and competence metrics for the TDS evaluation programme	A	5.1,5.6	1.Dev. Methods Life Cycle Model Validation	2y	2my	160	30
2.1.1.3	Evaluation of the Impact of the TDS on the Operating Environment	A	5.4,5.5	1.HCI	1y	1.5 my	120	-
2.1.1.4	Develop design methods & tools for task analysis	B	5.4,9.2	1.HCI	1y	2my	160	32
2.1.1.5	Optimisation of HCI design for tactical picture displays	B	5.4,5.5 10.4,10.7	1.HCI	1.5y	2.5my	200	52
2.1.1.6	Evaluation of the effects of operator interaction with the TDS	B	5.7	1.HCI	1y	2my	160	10
2.1.1.7	Validation of the TDS HCI	A	5.3,10.1	1.Develop. Methods Validation	2y	3my	240	-
2.1.1.8	To evaluate the TDS as data fusion system	A		1.Develop. Methods Validation 2. HCI	1y	2my	160	5

### 2.1.2 Laboratory Enhancements

Serial No	Description	Type	ARE Nos	Technical topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
2.1.2.1	Enhanced Situation Assessment Prototype	A	1.3	1. Knowledge Rep. Temporal Spatial Modal Reason Uncertainty	2y	7my	560	40
2.1.2.2	Enhanced Resource Allocation prototype	B	1.5	1. Knowledge Rep. Planning 2. Database/Kbase 3. HCI	1.5y	5my	400	40
2.1.2.3	Enhance TDS performance by concurrent processing	B		1. Hardware Archit Paradigms	3y	4my	320	125
2.1.2.4	HCI for Situation Assessment and Resource Allocation	A		1. HCI	3y	6my	480	77



2.1.3 Use Laboratory Prototypes

Serial No	Description	Type	ARE Nos	Technical Topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
2.1.3.1	Development of techniques for KBS maintenance	A	2.1,2.4	1.Develop. Methods Maintenance	2y	4my	320	60
2.1.3.2	Investigation of techniques for knowledge acquisition	B	2.7	1.Develop. Methods K. Acquisition	1.5y	3my	240	30
2.1.3.3	Development methods and tools for the <i>a posteriori</i> validation of knowledge based systems	B	2.5,2.6	1.Develop.Methods Validation Life Cycle	1.5y	3.5my	280	30
2.1.3.4	Exploration of appropriate techniques for explanation in situation assessment systems	B	9.3	1.HCI Cognitive Issues	2y	2my	160	32

**2.1.4 Other Prototypes**

Serial No	Description	Type	ARE Nos	Technical Topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
2.1.4.1	Exploration of Adaptive Interfaces for Command and Control Systems	B	10.2	1.HCI Modelling Issues	1y	1.5my	120	32
2.1.4.2	KBS for amphibious operations support	B	14.2,14.3	1.Knowledge Rep. Planning	2y	4.5my	360	40

**2.2 TMD****2.2.1 Lab Enhancement**

Serial No	Description	Type	ARE Nos	Technical topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
2.2.1.1	Evaluation and Assessment of the TMDD	B No longer valid	N/A		1.5y	3my	240	32
2.2.1.2	Integrated Data Fusion using the TMDD	B No longer valid	Related to data fusion experiments on TDS	1.H/W A - Paradigms 2. Neural Nets 3. DB/KBS coupling	3y	12my	960	40
2.2.1.3	Incorporation of Situation Assessment and Resource Allocation in the TMDD	B No longer valid	Related to TDS enhancements		2y	10my	800	
2.2.1.4	Integrate Discrimination into TMDD	B No longer valid		SDIO research with RAE	1.5y	2.5my	200	

## 2.2.2.2 Use Lab Prototypes

Serial No	Description	Type	ARE Nos	Technical topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
2.2.2.1	Specification of KBS for Command and Control Applications	A	2.6-LCM 5.1,5.6 evaluation	1. Dev Methods	1.5y	2.5my	200	30
2.2.2.2	Verification and Validation of 'Safety Critical' KBS	A	2.5 Val 5.1,5.6 evaluation (2.1.4.1)	1. Dev Methods	2y	6my	480	60
2.2.2.3	Investigation in to the Robustness of KBS Architectures	B	(1.1.1.1)	1. Dev Methods	2y	2my	160	-
2.2.2.4	Operational Adaptivity of KBS knowledge bases	B		1. Dev Methods	1y	4my	320	30
2.2.2.5	Integrating Knowledge Representations	B	(2.1,2.2,2.3) 3.3	1. Real Time 2. DB/KBS	0.75y	2.25my	180	30
2.2.2.6	Development of KBS not based on 'Expert' knowledge	B	SDIO interest	1. Dev methods	0.75y	1my	80	-
2.2.2.7	Real-Time Integrated Databases	A	SDIO interest	1. DB/KBS	1.5y	3my	240	40

**2.2.3 Stand-alone Prototypes**

Serial No	Description	Type	ARE Nos	Technical topics	Time	Effort	Manpower Cost (£K)	Other Cost (£K)
2.2.3.1	Adaptive Preferential Defence	B	React Res All 1.5	1. H/W A - Paradigms 2. RT/Syst Eng 3. KREP 4. HCI	1.5y	8.5my	680	60
2.2.3.2	Sensor Management	A	Dynamic scheduling? (Flypast +)	1. RT/Syst Eng 2. KREP 3. HCI 4. DB/KBS	2y	8.5my	680	90
2.2.3.3	Intention Prediction of Intelligently Manoeuvring Objects	B	Sit Ass R R All	1. KREP 2. HCI 3. DB/KBS 4. Naval (tracking)	2y	7my	560	40
2.2.3.4	Development Methods Prototype	A		1. Develop. Methods	2y	4my	320	30
2.2.3.5	Hybrid Approach to Data Fusion	A	TDS Improvements	1. H/W A	2.5y	5my	400	60

**3. Category 3 - Enabling Research****3.1 TMD and Naval****3.1.1 Adv Prototypes**

Serial No	Description	Type	ARE Nos	Technical Topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
3.1.1.1	Distributed Situation Assessment	A	BMC2 Prot 1.7 Extends Sit Ass in TDS/TMDD	1. DAI 2. KREP 3. HCI 4. DB/KBMS -KBMS	2y	5my	400	50
3.1.1.2	Co-operative Planning Aids for Command and Control	A	9.4,10.2,10.5 (1.4,1.5 re-visited)	1. HCI 2. KREP 3. DAI	2y	5.5my	440	40

**3.1.2 Other Projects**

Serial No	Description	Type	ARE Nos	Technical Topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
3.1.2.1	Application of Neural Networks for Data Fusion	A	leads on from existing ARE research	H/W Arch - NNets	3y	3my*	180	40
3.1.2.2	Application of Machine Learning for Data Fusion	A	new research proposal	Dev Methods (ML/KA)	3y	3my*	180	40
3.1.2.3	Application of Formal methods in KBS development	A	leads on from existing ARE research	Dev Methods (Formal Methods)	3y	4my (inc. 2my*)	280	-
3.1.2.4	Intelligent Training systems for Command and Control systems	B	7.2 8.1,8.4 13.1	1.HCI Organisational Issues	1.5y	4my	320	30

3.1.2.5	Genetic algorithms for Command and Control Applications	B		KRep and Dev Methods	3y	3my*	180	30
3.1.2.6	Machine Learning of Temporal Patterns for Command and Control	B		KRep and Dev Methods	3y	3my*	180	30

#### 4. Category 4 - Central Support

##### 4.1 TMD and Naval

Serial No	Description	Type	ARE Nos	Technical Topics	Time	Effort	Manpower Cost (£K)	Other Costs (£K)
4.1.1.1	Specification of Advanced Battle Management Prototype		BMC2 Prot 1.7		1y	2my	160	5
4.1.1.2	Scenario Generation and Data		4.1,4.2,4.3		3y	4.5my	360	
4.1.1.3	Provision of HCL investigation / trials facilities							
4.1.1.4	TDS Facilities management							
4.1.1.5	Programme Co-ordination							
4.1.1.6	Programme Evaluation							
4.1.1.7	TDS Trials Data Processing				1y	3my	240	